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Procedia Engineering 2 (2010) 2467–2472

Procedia Engineering

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8th Conference of the International Sports Engineering Association (ISEA)

Measurement of aerodynamic forces and flow field of a soccer ball in a wind tunnel for knuckle effect

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Received 31 January 2010; revised 7 March 2010; accepted 21 March 2010

Abstract

Wind tunnel experiments have been conducted to investigate the knuckle effect of a soccer ball. In the present experiment, we measured the surface pressure of a ball as well as aerodynamic forces, and made tuft grid visualization to investigate wake structure behind a ball. We are in particular interested in the seemingly random nature of the knuckle effect resulting from the movement of vortical structure behind a ball in the super critical Re range and in the detailed mechanism causing the knuckle effect. Discussion will also refers to knuckle balls of baseball and volleyball.

Kwywords: Soccer ball; knuckle effect, wind tunnel measurement, susrface pressure measurement, vortex shedding

1. Introduction

In ball games such as soccer, a ball flies in air, and thus the flight is interested from the aerodynamics point of view. On the occasion of FIFA World Cup in 2006, the design of ball was changed. The surface of the new ball (Teamgeist) was formed from less number of panels stuck together becoming smoother. As a result, strange ball trajectories where a ball irregularly shook and dropped just like a knuckle ball in baseball appeared more frequently.

The origin of the relating research was in those on the flow past a smooth sphere without spin at very high Reynolds numbers [1,2]. A modeling the soccer ball flight was also presented [3]. After World Cup 2006, aerodynamic studies of knuckle effect of a soccer ball have been intensively conducted by Asai et al. [4], Mizota et al. [5] and Iwai et al. [6], where the two are field researches [4,5] and the others are wind tunnel experiments [5,6]. A review of sports ball aerodynamics was also presented by Mehta [7,8]. It was described in our previous study [6] that the knuckle effect of a soccer ball (Teamgeist) in a low spinning-rate flight occurred in the super-critical Reynolds number (Re) range above $3.4\text{x}10^5$. In this Re range, a pair vortex structure composed of two attached

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doi:10.1016/j.proeng.2010.04.017

vortices was occasionally created, randomly rotates, disappears and then was re-formed at a frequency lower than about 1 Hz. These motions of pair vortex structure behind a ball induced the variation of the aerodynamic force on a ball, resulting in the knuckle effect. The knuckle ball had started from baseball game. However, similar ball behaviours are now found in volleyball and soccer games. We have conducted wind tunnel experiments to investigate the knuckle effect of a soccer ball without spin. In the present study as a new experiment, we used pressure transducers to measure the surface pressure of a ball as well as an aerodynamic force balance and a tuft grid to visualize the wake structure. We are interested in the seemingly random nature of the knuckle effect resulting from vortex shedding in the super-critical Re range and in the detailed mechanism causing the knuckle effect. Discussion will also refers to knuckle balls of baseball and volleyball.

2. Wind Tunnel Experiment

The overview of the wind tunnel experimental set-up is shown in Figure.1. The ball surface pressure measurement, in addition to the aerodynamic force measurement and the visualization of tuft movement, was conducted using a real-size model of a ball (Teamgeist). The detail of the wind tunnel experiment was described in our previous report [6]. The wind speed was set at 6 to 30 m/s corresponding to the Reynolds number of $0.8 \times 10^5 \sim 4.1 \times 10^5$. For the measurement of the surface pressure, a model ball with two pressure holes (A and B) apart by 90 deg. was used as shown in Figure 2. By changing the installation angle of the ball support stick that is connected with a 3-component balance, the angle of a pressure hole can be changed from –90 deg. through the stagnation point (0 deg.) to 90 deg. with respect to the air flow. A differential pressure transducer is located outside the ball, to which a pressure tube transmits the pressure. The tuft grid (950 mm square) is composed of fine machine cottons with a length of 25 mm that are tied at 31x33 grid points with an interval of 25 mm with the aid of a tiny steel wire ring for satisfactory tractability to local flow as seen in Figure 1. The timing of the data samplings of the tuft visualization and the measurements of the pressure and aerodynamic forces were synchronized. The balance measured only the drag *D* (in the flow direction *X*) and the side force *S* (*Y*-direction) for the present study.

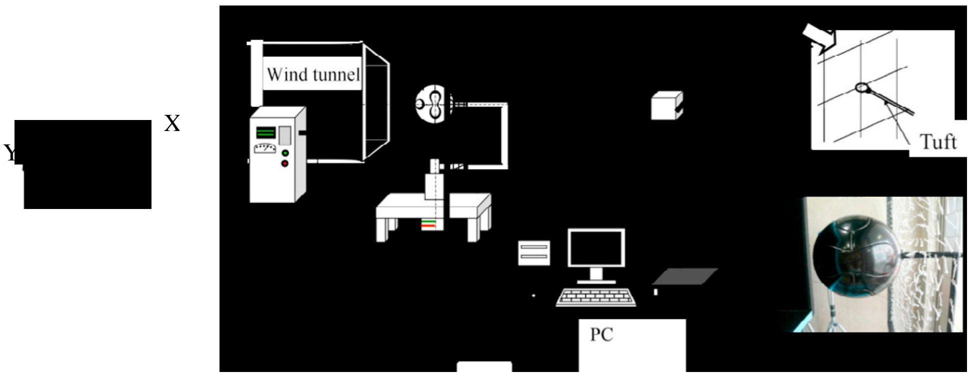

Figure 1. Wind tunnel experimental set-up (left) and the tuft grid (right).

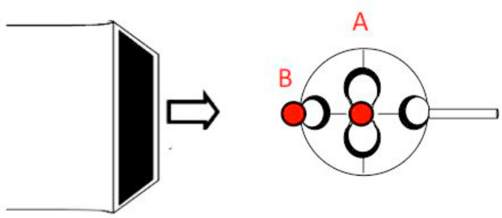

Figure 2. Two holes on the test ball surface for surface pressure measurement (side view). The holes with a diameter of 1 mm are connected to a differential pressure transducer by a tube with an inner diameter of 1 mm. The hole A at the front stagnation point and the B at 90 deg. from A for the ball supported from the back.

3. Experimental Results and Discussion

3.1. Time variations of C_s and C_p at Re=4.0x10^5.

Shown in Figure 3 is the time variations of the side force coefficient C_s (=$2S/\rho U^2 A$) and the pressure coefficient C_p (=$2p/\rho U^2$) measured at 90 deg from the stagnation point. Here S, p, U, ρ and A are the side force, the surface pressure, the air speed and density and the cross sectional area of the ball. It is readily seen that there is an perfect (negative) correlation between them. The negative correlation is just a consequence of the definition of the side force direction. The value of C_s changes around zero with a peak-to-peak value about 0.1. The periods of the large-scale variations of both coefficients are about 1 to 2 sec. On the left side of Figure 3, a tuft visualization picture is also shown, which is a superposed image of about 100 snap shots taken for 0.5 sec in the phases of high C_s value. In areas that extended in white, each tuft moved intensely. In these phases a pair of rather stable vortices located in a line of the upper and lower sides appears, which seems a pair of attached vortex to the ball. And the side force and the vortex-induced air velocity are also schematically shown in this figure. The FFT analysis results for the C_s and C_p data of Figure 3 are shown in Figure 4. It should be noted that the peaks around 11 Hz in the data of C_s is attributed to the oscillation of the ball support system. Significant peaks are found in the frequency range around 0.5 Hz. It may be concluded from the comparison with our previous wind tunnel experiment and some field experiments [4,6] that this kind of variation in the side force is the very cause of the knuckle effect on soccer ball flight.

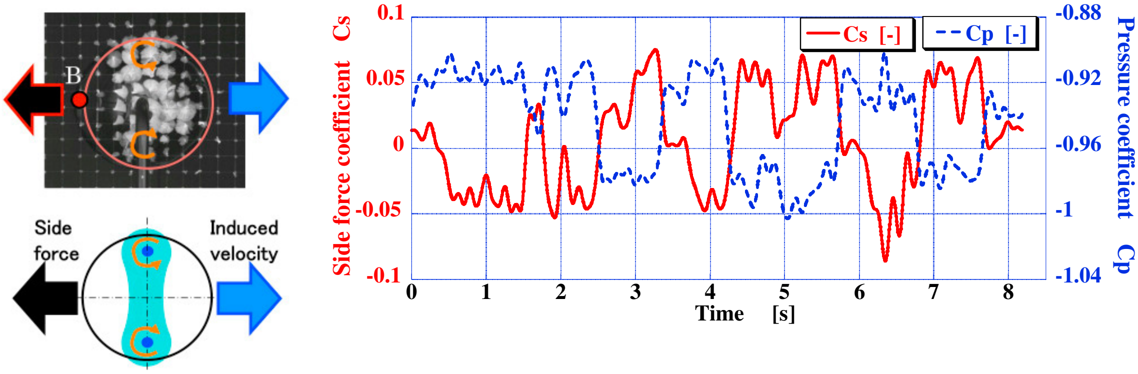

Figure 3. Time variations of the side force coefficient C_s and the pressure coefficient C_p measured by the pressure hole B at 90 deg from the front stagnation point in the case of super-critical Reynolds number Re=4.0x10^5. The tuft grid visualization result in the phases of high C_s in the data shown in this Figure is on the left.

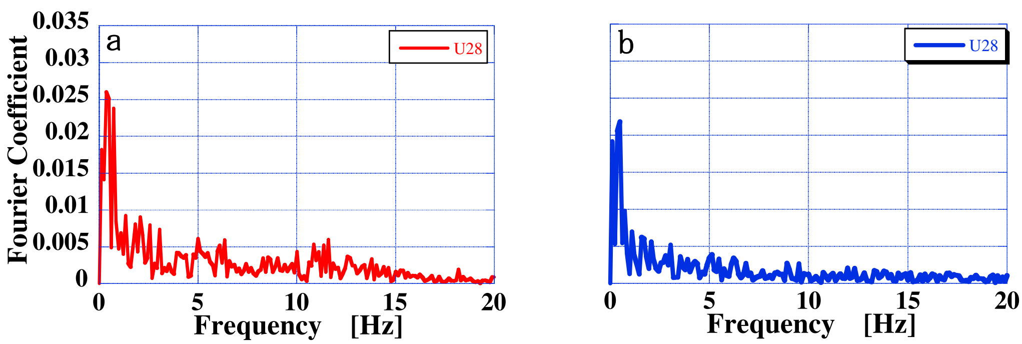

Figure 4. FFT analysis result for the data in Figure 3. Re=4.0x10^5 (super critical range). a: C_s, b: C_p.

3.2. Comparison of side force data for Re=1.1x10^5, 1.9x10^5 and 4.0x10^5

Figure 5 shows the comparison of the time variations of the side force for typical three Re ranges, sub-critical (Re=1.1x10^5), critical (1.9x10^5) and super-critical (4.0x10^5). It is evident the absolute values of the side force are considerably different depending on Re. It is found that the side force in the sub-critical and critical Re ranges is too small to cause a significant trajectory change in ball flight, the knuckle effect. To investigate the characteristic time for the variations, FFT analysis was attempted to the data in Figure 5, of which result is shown in Figure 6. Large peaks are found at 7 Hz for the sub-critical range data, and at less than 1 Hz for critical range data. In soccer games, particular variations of a ball flight trajectory occur one or two times during a flight for 1 or 2 sec. This result and some previous wind tunnel experimental data indicate that knuckle effect appears at a frequency about 0.5~1 Hz. We may conclude that 7 Hz variation in the sub-critical range is too rapid, and the amplitudes of the side force variation in the subcritical and critical ranges are too small for the effective knuckle ball for soccer ball flight. The present conclusion that the knuckle effect of a soccer ball occurs in the super-critical Re range is quite consistent with the result of our previous study [6]. It is, on the other hand, known that a knuckle ball in baseball appears at Re about 1.45x10^5 (~110 km/hr) in the sub-critical range and at Re about 1.6~2.4x10^5 in the critical range in volleyball. The critical Re is about 2.1x10^5 in the case of baseball and 1.5x10^5 in the case of volleyball. Therefore knuckle effects appearing in three ball flights are different phenomena from the view point of aerodynamics, though they look all similar in the phenomenon and thus are mixed-up in the knuckle effect.

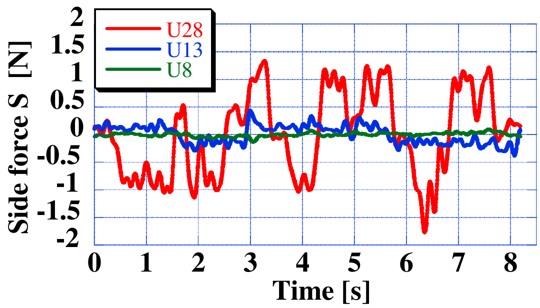

Figure 5. Comparison of the side force data for three Re-ranges; Re=1.1x10^5 (sub-critical range), Re=1.9x10^5 (critical range), Re=4.0x10^5 (super-critical range).

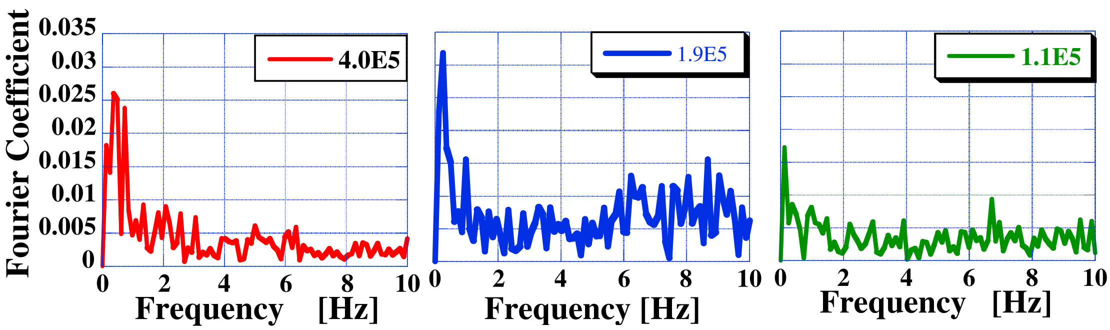

Figure 6. Comparison of the FFT results for the data in Figure 5. Re=1.1x10^5, Re=1.9x10^5, Re=4.0x10^5

3.3. Surface pressure measurement data

By changing the installation angle of the ball support stick, the angle of a pressure hole can be changed from –90 deg. through the stagnation point (0 deg.) to 90 deg. relatively to air flow. The data are presented in Figure 7 in an angle-C_p diagram for several values of Re. It is seen that the angle for laminar separation point is a little bit larger than 90 deg. irrespectively of Re for super-critical Re range, and it becomes small with the decrease of Re in the

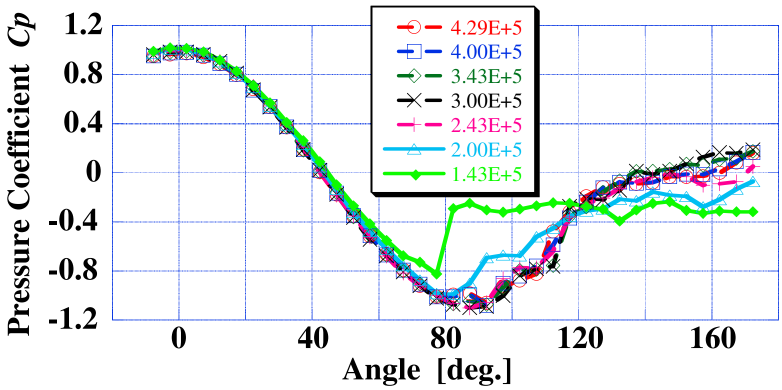

Figure 7. Surface pressure distribution in a form of angle-C_p diagram for several values of Re. The angle is measured from the stagnation point (0 deg.).

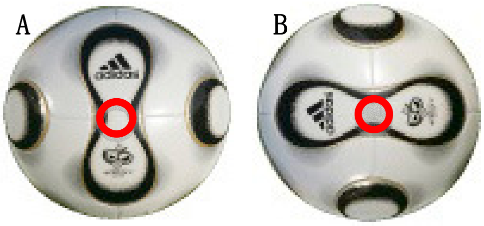

Figure 8. Two patterns, A and B, of seam lines around the pressure hole both at an angle of 90 deg. measured from the stagnation point.

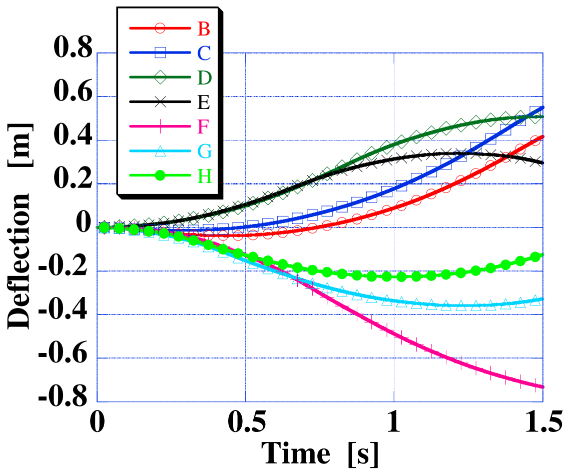

Figure 9. Simple calculation result of the deflection of a ball flight trajectory based on the present side force data. The calculation was carried out by numerically integrating the equation of motion with the time dependent external force for a flight time of 1.5sec. with an initial ball velocity of 30 m/s (Re=4.1×10^5).

range Re < 3.0×10^5. It had been concluded in the experiment using oil flow visualization by Taneda [2] that the angle of laminar separation for a smooth sphere was about 80 deg. almost independently of Re in the Re range

10^4~$3.5x10^5$, and for Re >$3.5x10^5$ the characteristic angles were about 110 deg. for laminar separation, 117 deg. for reattachment and 135 deg. for turbulent separation. In general, the angles of the present experimental ball seem slightly smaller by about 10 deg. than those in the Ref. [2]. This discrepancy may be attributed to the rough surface due to the seam lines of panels forming a soccer ball. It is interesting to note that the laminar separation angle was found to differ by about 10 deg. between the two seam line patterns as shown in Figure 8. The separation angle is smaller in the case of the pattern A. This suggests that slow variation of the surface pattern due to slow rotation delicately influences the side force variation as a cause of the knuckle effect during an actual soccer ball flight.

3.4. Prediction of deflection of ball flight path

Simple calculation is attempted to predict the deflection of a ball flight trajectory based on the present side force data. Typical results are shown in Figure 9. The calculation was carried out by numerically integrating the equation of motion with the time dependent external force for a flight time of 1.5sec. with an initial ball velocity of 30 m/s. It is seen in this result that each flight path may be largely different even for the same final deflection distance. The average of the absolute deflection for many calculation results is 10 cm for Re=$1.9x10^5$, 39 cm for Re=$3.0x10^5$, 46 cm for Re=$3.6x10^5$ and 82 cm for Re=$4.1x10^5$.

3. Conclusions

Wind tunnel experiments have been successfully conducted and the following conclusions were drawn:
1. The knuckle effect of a soccer ball appears in the super-critical Reynolds number range. It is found that in both sub-critical and critical Re ranges, the frequency range and the magnitude of the side force variation are not sufficient for the knuckle effect of a soccer ball.
2. The knuckle effect is caused by the large-scale variation of the side force (or the lift) in the frequency range of about 0.5~1.0 Hz. For this frequency range of variation, the correlation between the side force and the surface pressure variations is very high. Owing to this low frequency the knuckle ball looks like a random process in the appearance of an actual soccer ball flight for about 1 to 2 sec.
3. The knuckle effect is generated by the dynamic movement of a pair vortex structure composed of two attached vortices that is occasionally created, randomly rotates, disappears and then is re-formed. Therefore, it subtly changes depending on the seam pattern of a slowly rotating ball facing air flow.
4. The laminar separation line on a ball slightly moves towards the upstream side in the case of a soccer ball as compared with a smooth sphere due to the roughness of a soccer ball surface caused by the seam lines.
5. It is simulated that the absolute value of the deflection due to the knuckle effect becomes about 0.8 m for a flight for about 1.5 sec in the case of an initial velocity of 30 m/s.

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